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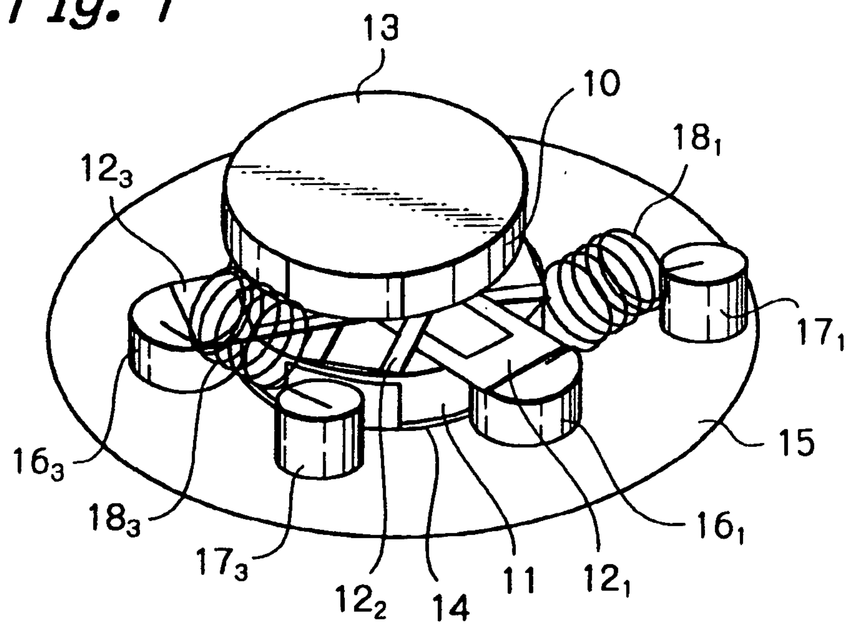
(54) **Lumped element circulator**

(57) A lumped element circulator having a plurality of operation bands, has a circulator element with a plurality of signal ports and a grounded terminal, and resonance circuits connected between the signal ports and the grounded terminal, respectively, each of the resonance circuits having a plurality of resonance points. The number of the operation bands is equal to the number of the resonance points of each of the resonance circuits.

Fig. 1



EP 0 903 802 A2

Description

FIELD OF THE INVENTION

[0001] The present invention relates to a lumped element circulator used as a high frequency circuit element in for example a portable or mobile communication equipment. Particularly, the present invention relates to a lumped element circulator operable in a plurality of frequency bands.

DESCRIPTION OF THE RELATED ART

[0002] A circulator is an element for giving non-reciprocal characteristics to a high frequency circuit so as to suppress reflecting waves in the circuit. Thus, standing waves can be prevented from generation resulting that stable operations of the high frequency circuit can be expected. Therefore, in recent portable telephones, such non-reciprocal elements are usually provided for suppress standing waves from generation.

[0003] Recently, demand for a portable telephone capable of operating in a plurality of different frequency bands (multi-bands telephone) has been increased in order to enable effective use of the portable telephone. However, the conventional circulator can be operated in only one frequency band. Thus, in order to operate in a plurality of frequency bands, it is necessary (A) to broaden the frequency bandwidth of the single band circulator by using an impedance matching circuit, or (B) to combine a plurality of single band circulators with a band-pass filter for individually operating the circulators.

[0004] According to the above-mentioned solution (A) where the frequency bandwidth of the single band circulator is broadened, a sufficiently wide bandwidth cannot be expected but only about 30 % of the center frequency can be broadened. Thus, as for a recent dual band portable telephone operable at dual frequencies which differ twice with each other, the solution (A) cannot be adopted.

[0005] According to the solution (B) where a plurality of single band circulators operating at different frequency bands are connected in parallel and are selected by filters and switching means, the dimension of the combined circuit becomes large. In addition, the impedance characteristics out of the bandwidths of the circulators interfere with each other causing the operating characteristics to become unstable.

SUMMARY OF THE INVENTION

[0006] It is therefore an object of the present invention to provide a lumped element circulator which alone can suppress standing waves from generation in a plurality of frequency bands.

[0007] According to the present invention, a lumped element circulator having a plurality of operation bands, has a circulator element with a plurality of signal ports and a grounded terminal, and resonance circuits connected between the signal ports and the grounded terminal, respectively, each of the resonance circuits having a plurality of resonance points. The number of the operation bands is equal to the number of the resonance points of each of the resonance circuits.

[0008] The invention focuses attention on that, in a lumped element circulator, difference between eigenvalues of the circulator element excited by positive and negative rotational eigenvectors is 120 degrees (in case of three port circulator) without reference to frequency. Thus, according to the invention, a network exhibiting a frequency performance for satisfying circulator conditions in a plurality of necessary frequency bands is connected to each port so that the circulator can operate in the plurality of frequency bands. This is realized by inserting a resonance circuit having a plurality of resonance points between each of the signal ports and the grounded terminal of the circulator element of the lumped element circulator.

[0009] As a result, according to the invention, a lumped element circulator alone can suppress any standing wave from generation in a plurality of frequency bands. Thus, in a high frequency circuit in a telephone which operates in a plurality of frequency bands such as a dual band telephone, the circulator according to the present invention can be alone used to suppress standing wave from generation in a plurality of frequency bands.

[0010] It is preferred that each of the resonance circuits is a series-parallel resonance circuit having at least one pair of a series resonance point and a parallel resonance point.

[0011] It is also preferred that the number of the operation bands is equal to the number of the pair of the series resonance point and the parallel resonance point plus one.

[0012] Furth r objects and advantages of the present invention will b apparent from the following description of the preferred embodiments of the invention as illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013]

Fig. 1 shows an oblique view schematically illustrating a structure of a dual band lumped element circulator of a preferred embodiment according to the present invention;
Fig. 2 shows an equivalent circuit diagram of the lumped element circulator of the embodiment shown in Fig. 1;
Fig. 3 shows an equivalent circuit diagram of a conventional lumped element circulator;
Figs. 4a and 4b show a sectional view and a top view illustrating a structure of an inductor part of the conventional lumped element circulator:
Fig. 5 shows an exploded oblique view illustrating a structure of a circulator element part of the conventional lumped element circulator;
Fig. 6 shows an oblique view illustrating an assembled structure in which resonance capacitors are connected to the circulator element shown in Fig. 5;
Fig. 7 illustrates magnetic field intensity when current flows through each signal port;
Fig. 8 shows a Smith chart illustrating variations of eigenvalues by connecting the resonance capacitors to satisfy the circulator conditions;
Fig. 9 shows a Smith chart illustrating that y_3-y_2 is independent of frequency;
Fig. 10 shows a circuit diagram illustrating a resonance circuit connected to each port of the lumped element circulator of the embodiment shown in Fig. 1;
Fig. 11 illustrates frequency-admittance characteristics of the resonance circuit shown in Fig. 10;
Fig. 12 illustrates transfer characteristics of a dual band lumped element circulator actually designed and fabricated; and
Fig. 13 shows a circuit diagram illustrating each of resonance circuits connected to a lumped element circulator of another embodiment according to the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0014] Fig. 1 schematically illustrates a structure of a three port type dual band lumped element circulator of a preferred embodiment according to the present invention.

[0015] In the figure, reference numerals 10 and 11 denote integrated ferromagnetic material disks, made of for example ferrite, sandwiching three pairs of two parallel drive conductors 12_1, 12_2 and 12_3 which are insulated from each other, 13 and 14 denote shielding electrodes formed on outer surfaces of the respective ferromagnetic material disks 10 and 11, 15 denotes a grounded electrode, 16_1, 17_1, 16_2 and 17_2 denote resonance capacitors, and 18_1 and 18_2 denote resonance coils, respectively. The pairs of drive conductors 12_1, 12_2 and 12_3 constitute three inductors which extend to three directions 120 degrees apart and form a trigonally symmetric shape.

[0016] The resonance capacitor 17_1 and the resonance coil 18_1 constitute a series resonance circuit. This series resonance circuit and the resonance capacitor 16_1 are connected in parallel between the signal port of the drive conductor pair 12_1 and the grounded electrode 15. Similar to this, the resonance capacitor 17_2 and the resonance coil 18_2 constitute a series resonance circuit. This series resonance circuit and the resonance capacitor 16_2 are connected in parallel between the signal port of the drive conductor pair 12_2 and the grounded electrode 15. Although it is hidden in Fig. 1, a series resonance circuit which is constituted by the resonance capacitor 17_3 and the resonance coil 18_3, and the resonance capacitor 16_3 (Fig. 2) are connected in parallel between the signal port of the drive conductor pair 12_3 and the grounded electrode 15. Excitation permanent magnets (not shown) are provided on the element 10 and under the element 11, respectively.

[0017] An equivalent circuit of the lumped element circulator of the embodiment of Fig. 1 is illustrated in Fig. 2. As will be understood from this figure, this lumped element circulator is equivalent to a circuit in which, between signal ports 21_1, 21_2 and 21_3 of an ideal circulator 20 and the grounded electrode 15, a series-parallel resonance circuit constituted by the resonance capacitor 16_1 with a capacitance C_0, the resonance capacitor 17_1 with a capacitance C_1, the resonance coil 18_1 with an inductance L_1 and an inductor L, a series-parallel resonance circuit constituted by the resonance capacitor 16_2 with a capacitance C_0, the resonance capacitor 17_2 with a capacitance C_1, the resonance coil 18_2 with an inductance L_1 and an inductor L, and a series-parallel resonance circuit constituted by the resonance capacitor 16_3 with a capacitance C_0, the resonance capacitor 17_3 with a capacitance C_1, the resonance coil 18_3 with an inductance L_1 and an inductor L are connected, respectively. The ideal circulator 20 is a virtual circuit element operating as a circulator over whole rang from z ro frequency to infinite frequency. Th circuit compos d of this ideal circulator 20 and the inductors L corresponds to non-reciprocal inductance of the meshed drive conductors 12_1, 12_2 and 12_3 constructed in the circulator lement.

[0018] According to the lumped el ment circulator of this mbodiment, inst ad of a capacitor, the resonanc circuit

providing a necessary effective capacitance at required frequencies is connected between each of the signal ports 21_1, 21_2 and 21_3 and the grounded electrode 15. Thus, this lumped element circulator can operat as a circulator in a plurality of frequency bands, as described hereinafter in detail.

[0019] An equivalent circuit of a conventional lumped element circulator is illustrated in Fig. 3. As shown in this figure, the conventional lumped element circulator is equivalent to a circuit in which parallel resonance circuits 32_1, 32_2 and 32_3 with a center frequency f_0 are connected to signal ports 31_1, 31_2 and 31_3 of an ideal circulator 30, respectively. The ideal circulator 30 is a virtual circuit element operating as a circulator over whole range from zero frequency to infinite frequency. The circuit composed of this ideal circulator 30 and inductors L in the parallel resonance circuits 32_1, 32_2 and 32_3 corresponds to non-reciprocal inductance of meshed drive conductors constructed in a circulator element of the conventional lumped element circulator.

[0020] Figs. 4a and 4b illustrate a structure of an inductor part of the conventional lumped element circulator, Fig. 5 illustrates a structure of a circulator element part of this conventional lumped element circulator, and Fig. 6 illustrates an assembled structure in which resonance capacitors are connected to the circulator element shown in Fig. 5.

[0021] As will be apparent from these figures, the structure of the circulator element part of this conventional lumped element circulator is the same as that of the lumped element circulator of the embodiment shown in Fig. 1.

[0022] Namely, integrated ferromagnetic material disks 40 and 41 sandwich three pairs of two parallel drive conductors 42_1, 42_2 and 42_3 which are insulated from each other. Shielding electrodes 43 and 44 are formed on outer surfaces of the respective ferromagnetic material disks 40 and 41. The drive conductor pairs 42_1, 42_2 and 42_3 constitute three inductors which extend to three directions 120 degrees apart and form a trigonally symmetric shape. Resonance capacitors 46_1, 46_2 and 46_3 are connected between signal ports 31_1, 31_2 and 31_3 of the drive conductor pairs 42_1, 42_2 and 42_3, respectively. Excitation permanent magnets 47 and 48 are provided on the element 40 and under the element 41, respectively.

[0023] In Fig. 4a, a section of the inductor (drive conductor 42_1) connected to one signal port (signal port 31_1 for example) and excited magnetic fields are illustrated. Suppose that inductance of this inductor (drive conductor pair 42_1) is L_0, magnetic field 49 excited by current flowing through the remaining two inductors (drive conductor pairs 42_2 and 42_3) will cross the inductor 42_1 connected to the signal port 31_1. Thus, inductance viewed from this signal port 31_1 has to be calculated in consideration of the influence of the magnetic field 49.

[0024] In a n-ports circuit, reflection coefficients of respective signal ports can be equalized with each other by applying specially combined advance waves to the respective signal ports. Vectors indicating the advance waves which satisfy this condition are called as eigenvectors, and the reflection coefficients are called as eigenvalues. In the n-ports circuit, n eigenvectors and n eigenvalues corresponding to the respective vectors are existed. Therefore, in the three ports circulator, three eigenvectors u_1, u_2 and u_3 and three eigenvalues s_1, s_2 and s_3 corresponding to the respective vectors are existed. These eigenvectors should have the following values.

$$\vec{u}_1 = \frac{1}{3}\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, \quad \vec{u}_2 = \frac{1}{3}\begin{pmatrix} 1 \\ e^{-j\frac{2\pi}{3}} \\ e^{j\frac{2\pi}{3}} \end{pmatrix}, \quad \vec{u}_3 = \frac{1}{3}\begin{pmatrix} 1 \\ e^{j\frac{2\pi}{3}} \\ e^{-j\frac{2\pi}{3}} \end{pmatrix} \qquad (1)$$

$$s_2 = s_1 e^{j\frac{2\pi}{3}}, \qquad s_3 = s_1 e^{-j\frac{2\pi}{3}}$$

[0025] Admittances y_1, y_2 and y_3 with respect to these reflection coefficients are given as following equation (2);

$$y_i = Y_c \frac{1 - s_i}{1 + s_i}, \ [i = 1, 2, 3] \qquad (2)$$

where Y_c is the t rminal admittanc of each port.

[0026] In case that the magnetic field H_1 excited by current j_1 flowed into the signal port 31_1 of the conventional lumped element circulator shown in Figs. 3 to 6 is as indicated by the dotted line arrow 49 in Fig. 4b, the magnetic fields H_2 and H_3 excited by currents j_2 and j_3 flowed into the ports 31_2 and 31_3 respectively are represented, by using H_1 as a reference, as shown in Fig. 7. Thus, it is apparent that H_1 direction components of the magnetic fields H_2 and H_3 are represented as;

$$
\begin{aligned}
-\dot{H}_2 \cos\frac{\pi}{3} &= -\frac{1}{2}\dot{H}_2 \\
-\dot{H}_3 \cos\frac{\pi}{3} &= -\frac{1}{2}\dot{H}_3
\end{aligned}
\qquad (3)
$$

and then, by adding the magnetic field H_1, the magnetic field H is represented by following equation (4).

$$
H = \dot{H}_1 - \frac{1}{2}(\dot{H}_2 + \dot{H}_3) \qquad (4)
$$

[0027] Thus, excitation magnetic fields H^1, H^2 and H^3 for the respective eigenvectors u_1, u_2 and u_3 are obtained by following equations (5);

$$
\begin{aligned}
H^1 &= \dot{H}_1 - \frac{1}{2}(\dot{H}_1 + \dot{H}_1) = 0 \\
H^2 &= \dot{H}_1 - \frac{1}{2}\left(e^{-j\frac{2\pi}{3}}\dot{H}_1 + e^{j\frac{2\pi}{3}}\dot{H}_1\right) = \frac{3}{2}\dot{H}_1 \\
H^3 &= \dot{H}_1 - \frac{1}{2}\left(e^{-j\frac{2\pi}{3}}\dot{H}_1 + e^{j\frac{2\pi}{3}}\dot{H}_1\right) = \frac{3}{2}\dot{H}_1
\end{aligned}
\qquad (5)
$$

therefore, inductances of the conductors viewed from the respective signal ports L_1, L_2 and L_3 for the eigenvectors u_1, u_2 and u_3 are given as following equation (6);

$$
L_1 = 0, \qquad L_2 = L_3 = \frac{3}{2}L_0 \equiv \xi \qquad (6)
$$

where L_0 is the inductance of the shorten end two parallel conductors connected to one signal port when another conductors are open at end behalf of shorten.

[0028] The loading admittances of the ferromagnetic material disk or the ferrite, in other words the admittances of the part of the inductor y_{L1}, y_{L2} and y_{L3} for the eigenvectors u_1, u_2 and u_3 are therefore given as following equation (7);

$$
\begin{aligned}
y_{L1} &= \infty \\
y_{L2} &= \frac{1}{j\omega\xi\mu_+} \\
y_{L3} &= \frac{1}{j\omega\xi\mu_-}
\end{aligned}
\qquad (7)
$$

where μ_+ and μ_- are the positive and the negative polarized relative permeabilities. It is to be noted that the magnetic filed for exciting the eigenvectors u_2 and u_3 become the positive and negative rotational magnetic fields with respect to the externally applied D.C. magnetic field. The values $\mu +$ and $\mu -$ are obtained by Polder's equation as following equation (8);

$$
\begin{aligned}
\mu_\pm &= 1 + \frac{P}{\sigma \mp 1} \\
P = \frac{|\gamma|\, 4\pi M_\delta}{\omega}&, \qquad \sigma = \frac{|\gamma|\, H_i}{\omega}
\end{aligned}
\qquad (8)
$$

where $4\pi M_s$ is the saturation magnetization of the ferrite, H_i is the internal D.C. magnetic field in the ferrite, and γ is the gyromagnetic constance. By using the equation (8), following equation (9) can be obtained.

$$\frac{1}{\mu_-}-\frac{1}{\mu_+}=\frac{\sigma+1}{\sigma+1+P}-\frac{\sigma+1}{\sigma-1+P}=\frac{2P}{(\sigma+P)^2-1} \quad (9)$$

[0029] When it is operated under a magnetic field which is higher than the ferromagnetic resonance field (under above-resonance operation), for example operated in the lumped element circulator, there is a relationship of $(\sigma+P)^2>>1$. Therefore, in this case, the equation (9) can be made approximations as follows.

$$\frac{1}{\mu_-}-\frac{1}{\mu_+}\doteq\frac{2\omega|\gamma|4\pi M_\delta}{|\gamma|^2(H_i+4\pi M_\delta)^2}=\frac{8\omega\pi M_\delta}{|\gamma|(H_i+4\pi M_\delta)^2} \quad (10)$$

[0030] As a result, a value of $(1/j_\omega\xi\mu_+)-(1/j_\omega\xi\mu_-)$ can be obtained by following equation (11);

$$\frac{1}{j\omega\xi\mu_-}-\frac{1}{j\omega\xi\mu_+}=y_{L3}-y_{L2}=\frac{8\pi M_\delta}{j\xi|\gamma|(H_i+4\pi M_\delta)^2} \quad (11)$$

where the value of $j(y_{L2}-y_{L3})$ is not related to frequency. This result suggests that the difference between the eigenvalues s_2 and s_3 in the circulator under excitation of the eigenvectors u_2 and u_3 is independent to frequency. In the lumped element circulator, the inductance L_1 for the eigenvector u_1 is 0 as indicated in the equation (6). Thus, the eigenvalue s_1 is located at the right end point (1,0) on the Smith chart and independent to frequency. Therefore, after the applied magnetic field is adjusted so that the eigenvalues s_2 and s_3 have 120 degrees apart from each other on the Smith chart, if the position of the eigenvalues s_2 and s_3 are moved by adding capacitors to the respect signal ports so that the angle of each of the eigenvalues s_2 and s_3 with respect to the eigenvalue s_1 becomes 120 degrees as shown in Fig. 8, a complete circulator at that frequency can be obtained.

[0031] In order to realize a circulator, it is necessary for the lumped element circulator that the eigenvalues s_2 and s_3 have to satisfy following equation (12) derived from the conditions of the eigenvalue s_1 expressed by the equation (7) with reference to the equation (1).

$$s_1=-1,\quad s_2=e^{-j\frac{\pi}{3}},\quad s_3=e^{j\frac{\pi}{3}} \quad (12)$$

[0032] Eigenadmittances satisfying this condition are given as following equation (13).

$$y_1=\infty,\quad y_2=-j\frac{Y_c}{\sqrt{3}},\quad y_3=j\frac{Y_c}{\sqrt{3}} \quad (13)$$

[0033] Thus,

$$y_3-y_2=j\frac{2Y_c}{\sqrt{3}} \quad (14)$$

is given. Substituting this equation (14) into the equation (11), following equation (15) is obtained.

$$\xi=\frac{4\sqrt{3}\pi M_\delta Z_c}{|\gamma|(H_i+4\pi M_\delta)^2} \quad (15)$$

[0034] It should b noted from the equation (13) that the circulator has to satisfy $y_2+y_3=0$. This is equivalent to that, as shown in Fig. 9, the admittances on th Smith chart are replaced as $y_{L2}\rightarrow y_2$ and $y_{L3}\rightarrow y_3$ with keeping the r lation of the equation (14) to satisfy the circulator conditions by adding resonanc capacitors to the signal ports, respectively.

Therefore, the condition of $(y_2+y_3)/2=\omega C$ should be held. This condition can be obtained as follows by using the equation (8) and the above-resonance operation conditions of σ^2, $\sigma P>>1$.

$$\frac{y_{L3}+y_{L2}}{2}=\frac{1}{j2\omega\xi}\left(\frac{1}{\mu_-}+\frac{1}{\mu_+}\right)=\frac{\sigma^2-1}{j\omega\xi\,(\sigma^2-1+\sigma P)}$$

$$\fallingdotseq\frac{\sigma}{j\omega\xi\,(\sigma+P)}=\omega C \qquad (16)$$

[0035] As a result, the capacitance C can be obtained by following equation (17).

$$C=\frac{\sigma}{\omega^2\xi(\sigma+P)}=\frac{H_i}{\omega^2\xi(H_i+4\pi M_\delta)} \qquad (17)$$

If a resonance capacitor with the capacitance C which is inversely proportional to ω^2 is connected to each port, it is possible to obtain a circulator. In other words, if a circuit exhibiting a required effective capacitance at required frequencies is connected each port of the circulator element, a desired circulator having a plurality of operating frequency bands can be realized.

[0036] Suppose that a circulator is realized by connecting a circuit exhibiting the capacitance C at the frequency f_1 to each port. A circulator operating at both frequencies f_1 and f_2 can be obtained by connecting to each port of this circulator a circuit exhibiting a capacitance C at the frequency f_1 and also exhibiting a capacitance $(f_1/f_2)^2C$ at the frequency f_2.

[0037] A series-parallel resonance circuit shown in Fig. 10 is capacitive under and above the resonance frequency. Thus, if the operating frequencies of this circuit are adjusted at frequencies under and above its series-parallel resonance frequency, this circuit will meet the above-mentioned condition. An admittance y of this series-parallel resonance circuit is given as;

$$y=j\omega C_0+\frac{1}{j\omega L_1-\frac{1}{j\omega C_1}} \qquad (18)$$

which is expressed as the frequency-admittance characteristics shown in Fig. 11. This equation (18) can be rewritten as;

$$y=\frac{\omega C_0(\omega_p^2-\omega^2)}{\omega_\delta^2-\omega^2} \qquad (19)$$

where ω_s and ω_p are angular frequencies of the series resonance and the parallel resonance, respectively, and

$$\omega_\delta^2=\frac{1}{L_1C_1},\qquad \omega_p^2=\omega_\delta^2\left(1+\frac{C_1}{C_0}\right).$$

[0038] In the case of $f_2=2f_1$, a necessary capacitance is C/4 and therefore the admittances at the frequencies f_1 and f_2 are expressed as ω_1C and $\omega_2C=\omega_1C/2$, respectively. Substituting these conditions into the equation (19), following equations are obtained.

$$\omega_1 C = \frac{\omega C_0 (\omega_p^2 - \omega^2)}{\omega_\delta^2 - \omega^2}$$

$$\frac{\omega_1 C}{2} = \frac{\omega C_0 (\omega_p^2 - \omega^2)}{\omega_\delta^2 - \omega^2} \qquad (20)$$

[0039] Since the number of unknowns is more than the number of equations in the equation (20), some constants in the equation can be arbitrarily determined. If x and y are expressed as;

$$x = \frac{\omega_\delta}{\omega_1}, \qquad y = \frac{\omega_p}{\omega_1}$$

in case of $f_2=2f_1$, y is given by following equation (21).

$$y \sqrt{5 - \frac{4}{x^2}} \qquad (21)$$

[0040] The x and y are restricted as $1<x<2$ and $1<y<2$ because of the predetermined relation between the operation frequencies and, as will be apparent from Fig. 11, the solution will be unstable when x approaches 1 or y approaches 2. By determining y after x is determined to an appropriate value, C_0, C_1 and L_1 can be obtained from the equation (20) as follows.

$$C_0 = C\frac{x^2 - 1}{y^2 - 1}$$

$$C_1 = C_0\left\{\frac{y^2}{x^2} - 1\right\} = C\frac{x^2 - 1}{y^2 - 1}\left\{\frac{y^2}{x^2} - 1\right\} \qquad (22)$$

$$L_1 = \frac{1}{\omega_\varepsilon^2 \cdot C_1} = \frac{1}{(x \cdot \omega_1)^2 \cdot C_1}$$

[0041] A dual band lumped element circulator according to this embodiment is practically designed and fabricated. To design the circulator, when we choose values of $4\pi M_3=400$ Gauss, $f_1=300$ MHz, $\alpha=3.5$ and $Zc=50\ \Omega$, P, $\omega\xi$ and ξ are calculated as follows.

$$P = \frac{2.8 \times 450}{300} = 4.20$$

$$\omega\xi = \frac{\sqrt{3} \times 4.20 \times 50}{(3.50+4.20)^2} = 6.13\ (\Omega)$$

$$\xi = 3.25\ (\text{nH})$$

Thus, the r sonance capacitance C can be obtained by using the equation (17) as follows.

$$C=\frac{3.5}{(2\pi\times300\times10^{6})^{2}\times3.25\times10^{-9}\times(3.5+4.20)}$$
$$=39.3\ (pF)$$

A circulator element which satisfies this condition is fabricated and thus a dual band lumped element circulator operable at octave frequencies of 300 MHz and 600 MHz is formed. Circuit constants of the resonance capacitance circuit connected to each port of the circulator instead of the conventional capacitor are determined with reference to the equation (22) as follows.

$$C_0 = 39.3 \times \frac{1.30^2 - 1}{1.62^2 - 1} = 16.7\ (pF)$$

$$C_1 = 16.7 \times \left(\frac{1.62^2}{1.30^2} - 1 \right) = 9.2\ (pF)$$

$$f_\delta = 1.30 \times 300 = 390\ (MHz)$$

$$L_1 = \frac{1}{(2\pi \times 390 \times 10^6)^2 \times 9.2 \times 10^{-12}} = 18.0\ (nH)$$

[0042] The dual band circulator thus fabricated has a transfer characteristics as shown in Fig. 12. As will be understood from the figure, this measured transfer characteristics matches with the designed characteristics very well.

[0043] The aforementioned embodiment concerns a dual band circulator with two operation bands. It is known however that in a two-terminal resonance circuit with a plurality of resonance points, capacitive regions can be made by the number equal to the number of its resonance point pairs plus one. Therefore, it is apparent that a circulator with three or more operation bands at desired frequencies can be constructed by modifying the aforementioned embodiment.

[0044] Fig. 13 illustrates a resonance circuit connected to each port of a lumped element circulator of another embodiment according to the present invention.

[0045] As shown in the figure, this series-parallel resonance circuit has a series resonance circuit constituted by a resonance coil 131 with an inductance L1 and a resonance capacitor 132 with a capacitance C1 connected in series, a resonance capacitor 133 with a capacitance C_0 connected in parallel with the series resonance circuit, a resonance coil 134 with an inductance L_2 connected in series with the series resonance circuit, and a resonance capacitor 135 with a capacitance C_2 connected in parallel with the resonance coil 134 and the series resonance circuit. This two-terminal series-parallel resonance circuit is connected between each signal port and the grounded electrode of the circulator as well as the aforementioned embodiment.

[0046] This series-parallel resonance circuit has two pairs of series resonance point and parallel resonance point, and therefore is used for a circulator which requires three operation bands.

[0047] Many widely different embodiments of the present invention may be constructed without departing from the spirit and scope of the present invention. It should be understood that the present invention is not limited to the specific embodiments described in the specification, except as defined in the appended claims.

Claims

1. A lumped lem nt circulator having a plurality of operation bands, comprising:

   a circulator element with a plurality of signal ports and a grounded terminal; and

resonance circuits connected between said signal ports and said grounded terminal, respectively, each of said resonance circuits having a plurality of resonance points,
the number of said operation bands being equal to the number of said resonance points of each of the resonance circuits.

2. The circulator as claimed in claim 1, wherein each of said resonance circuits is a series-parallel resonance circuit having at least one pair of a series resonance point and a parallel resonance point.

3. The circulator as claimed in claim 2, wherein the number of said operation bands is equal to the number of the pair of the series resonance point and the parallel resonance point plus one.

Fig. 1

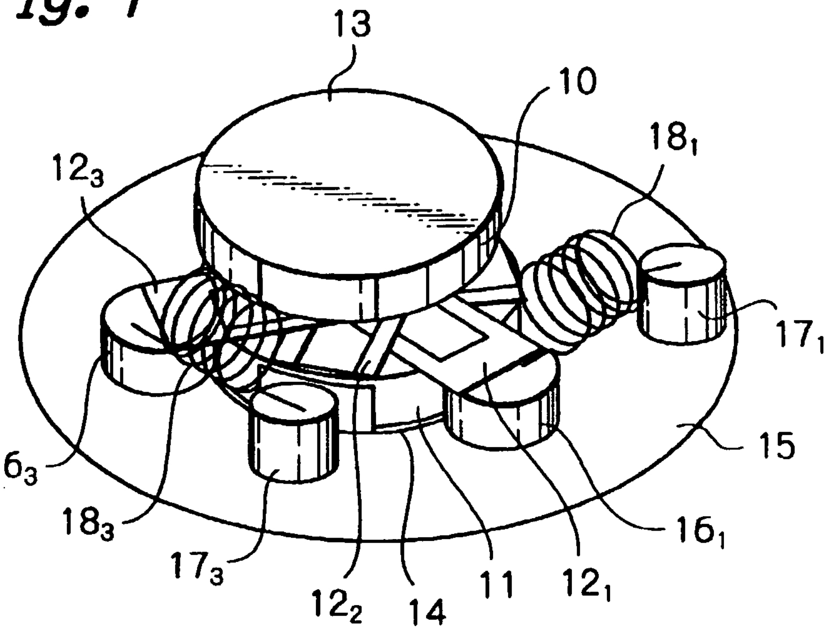

13
10
18_1
12_3
17_1
15
16_3
18_3
16_1
17_3
11
12_1
12_2
14

Fig. 2

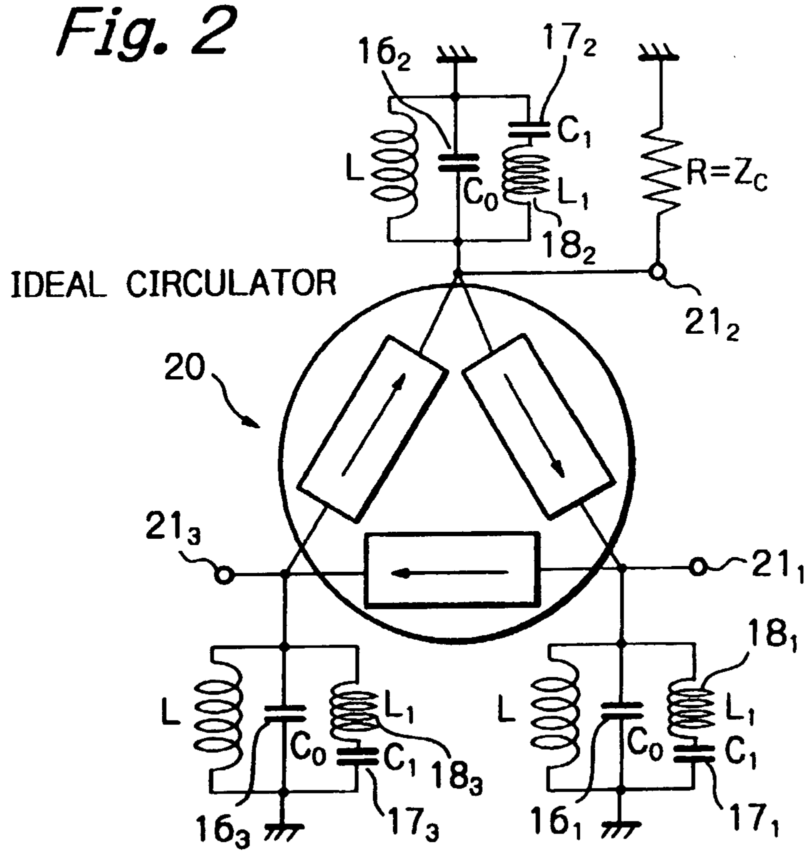

16_2
17_2
C_1
L
C_0
L_1
$R=Z_C$
18_2
IDEAL CIRCULATOR
21_2
20
21_3
21_1
18_1
L
L_1
C_0
C_1
18_3
L
L_1
C_0
C_1
16_3
17_3
16_1
17_1

Fig. 3

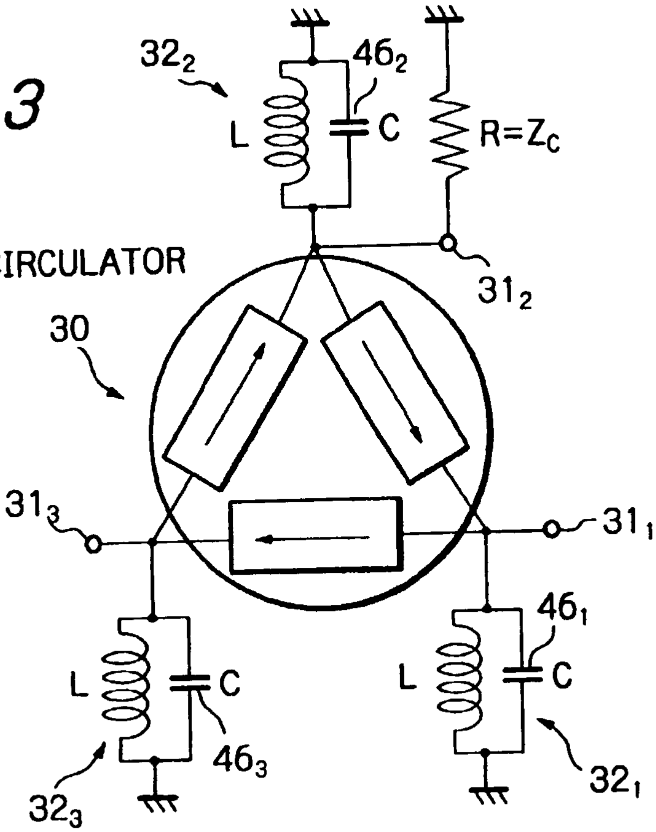


Fig. 4a

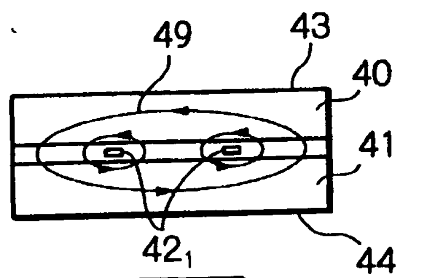


Fig. 4b

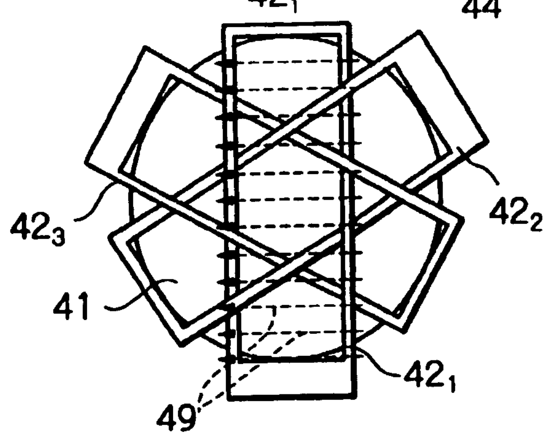


Fig. 5

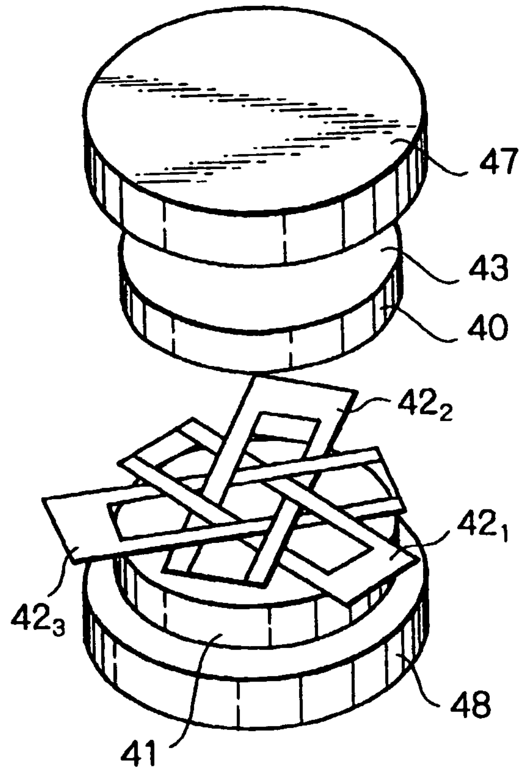


Fig. 6

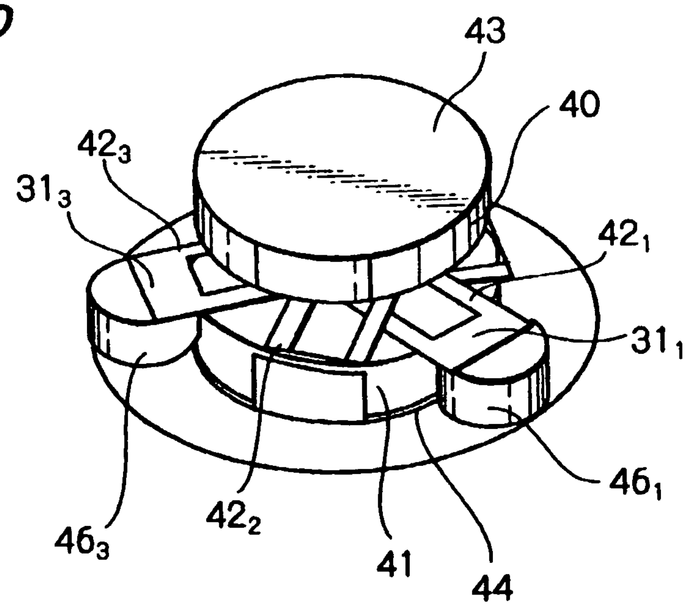


Fig. 7

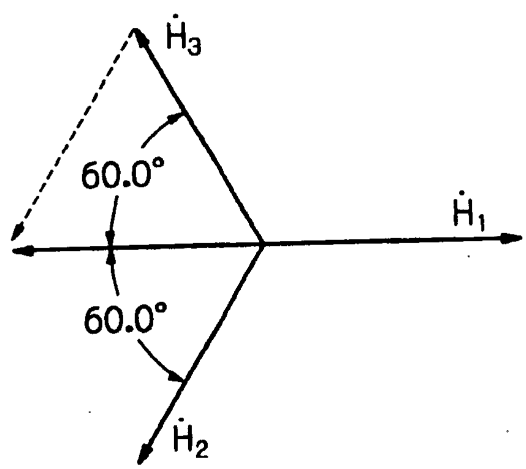
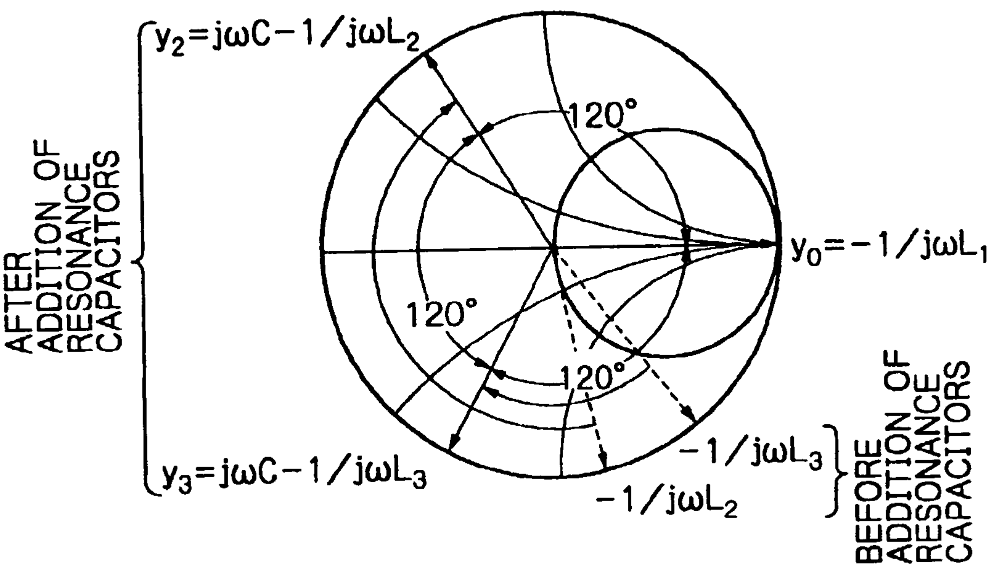
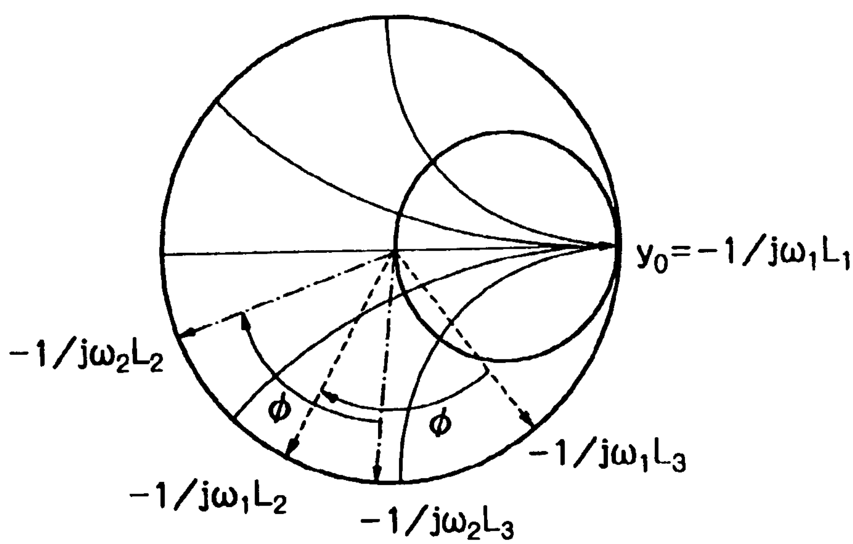


Fig. 8



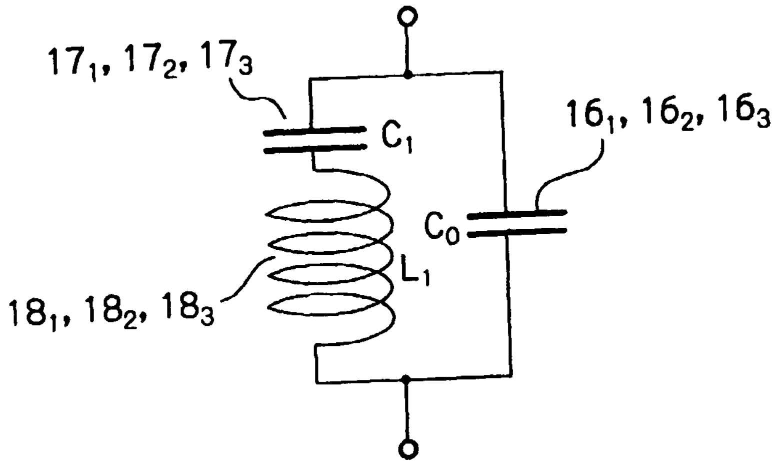
$y_2=j\omega C-1/j\omega L_2$
120°
120°
120°
$y_0=-1/j\omega L_1$
AFTER ADDITION OF RESONANCE CAPACITORS
$y_3=j\omega C-1/j\omega L_3$
$-1/j\omega L_3$
$-1/j\omega L_2$
BEFORE ADDITION OF RESONANCE CAPACITORS

Fig. 9



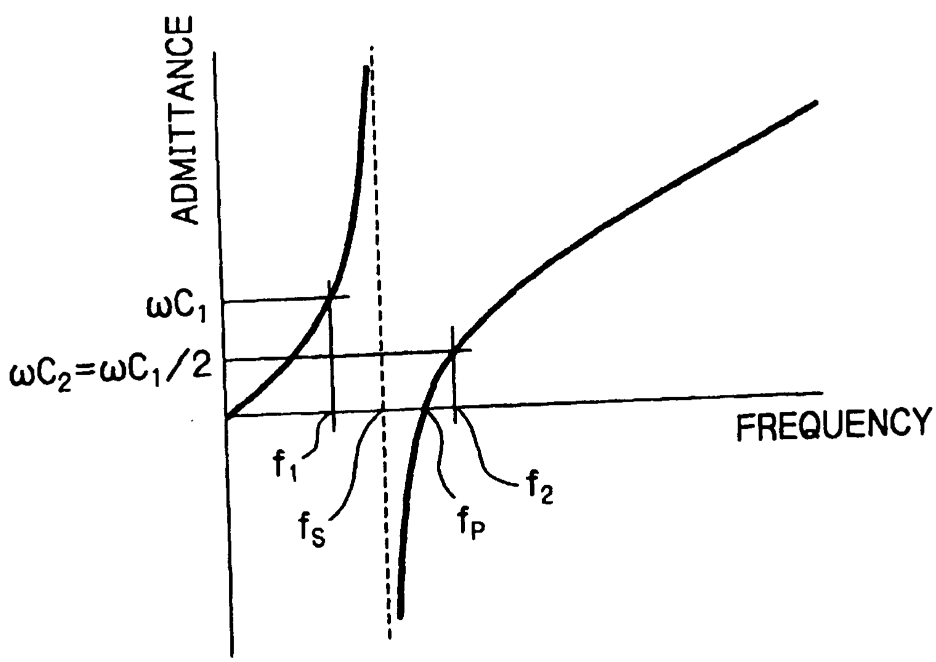
$y_0=-1/j\omega_1 L_1$
$-1/j\omega_2 L_2$
ϕ
ϕ
$-1/j\omega_1 L_3$
$-1/j\omega_1 L_2$
$-1/j\omega_2 L_3$

Fig. 10



$17_1, 17_2, 17_3$
C_1
$16_1, 16_2, 16_3$
C_0
L_1
$18_1, 18_2, 18_3$

Fig. 11



ADMITTANCE
ωC_1
$\omega C_2=\omega C_1/2$
FREQUENCY
f_1
f_S
f_P
f_2

Fig. 12

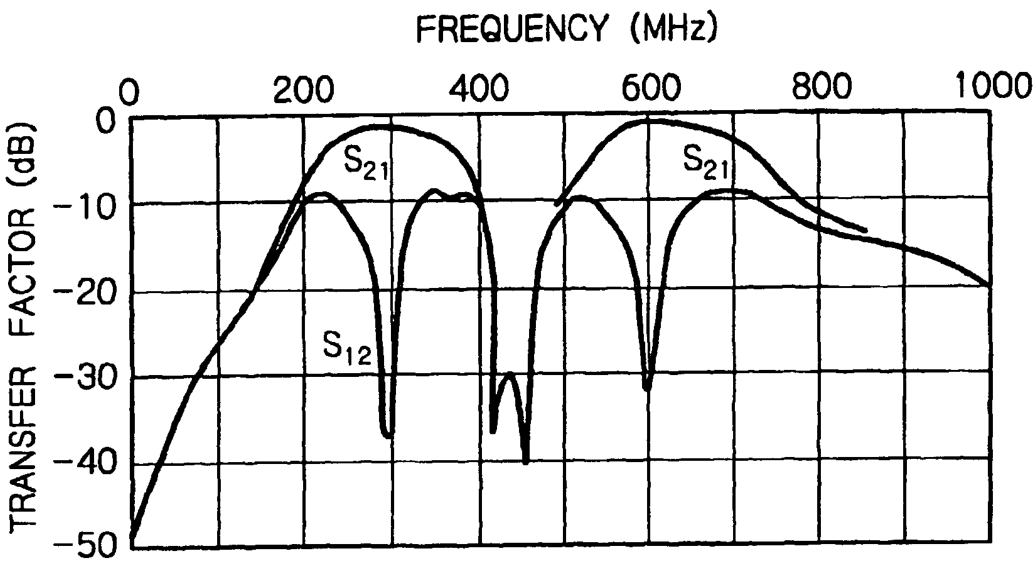
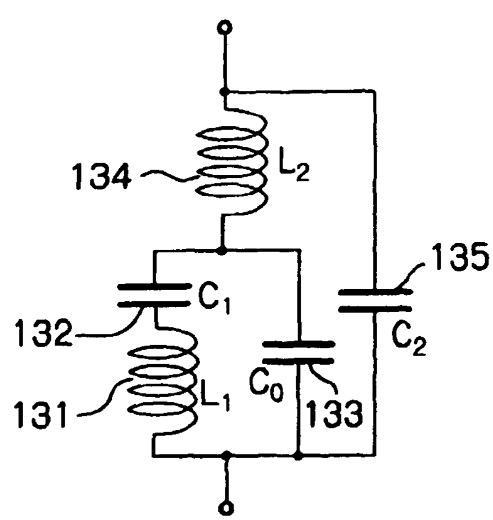

FREQUENCY (MHz)
0
200
400
600
800
1000
TRANSFER FACTOR (dB)
0
-10
-20
-30
-40
-50
S21
S21
S12

Fig. 13


134
L2
135
C1
132
C2
C0
131
L1
133